Groundwater heat pump systems diffusion and groundwater resources protection

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Geothermal Energy, being a clean and sustainable source of energy, is gaining importance worldwide due to various reasons. Geothermal power can be generated throughout the year on twenty four hour basis as it's not much dependent on ambient temperature and weather conditions.
Recently there is an increased interest in exploitation of low enthalpy geothermal resources for other applications such as geothermal space heating and cooling for domestic, industrial and commercial applications.
GroundWater Heat Pump systems (GWHPs) extract water from one or more wells, pass it through a heat exchanger or a heat pump, which either extracts heat from, or rejects heat, and discharge water back into the aquifer or nearby surface water.
This reinjection disturbs the natural aquifer temperature, producing a local temperature anomalies (cold or heat plume) known as the thermal affected zone (TAZ).
Moreover, it is important to know if the TAZ can interfere with downgradient pre-existing plants or subsurface infrastructure or with the plant itself (thermal feedback). It is then important to know, even before constructing a GWHP system, the future TAZ extent around the planned injection point.
Due to these risks, the increasing number of GWHP systems enforces the need for new criteria to develop subsurface energy policies that allow planning their spatial distribution. To obtain these sustainability criteria, the results of different dedicated studies are here proposed, in order to optimize the design and operation of GWHP systems.

Keywords: *geothermal energy, thermal feedback, groundwater heat pumps system, groundwater protection, thermal affected zone modeling.*

Diffusione dei sistemi di pompa di calore per acque sotterranee e protezione delle risorse idriche sotterranee. *L'energia geotermica, essendo una fonte di energia pulita, sta guadagnando importanza in tutto il mondo a causa di varie ragioni. L'energia geotermica può essere generata durante l'anno su ventiquattro ore perché non dipende molto dalla temperatura ambientale e dalle condizioni meteorologiche.*
Recentemente si registra un maggiore interesse nello sfruttamento delle risorse geotermiche a bassa entalpia per altre applicazioni come il riscaldamento ed il raffrescamento di edifici sia ad uso domestico che industriali e commerciali.
I sistemi a pompe di calore (GWHPs) estraggono acqua dal primo acquifero attraverso l'uso di pozzi, tale acqua passa attraverso uno scambiatore o una pompa di calore dove poi viene estratto calore e/o reimmesso calore a seconda della stagionalità ed infine l'acqua viene scaricata o in acquifero superficiale tramite un pozzo o in corpo idrico superficiale. Questa immissione di acqua in acquifero superficiale provoca un'anomalia termica (a seconda che la plume sia più calda o più fredda rispetto alla temperatura indisturbata dell'acquifero) la plume viene anche detta Thermal Affected Zone (TAZ). Inoltre è importante sapere se la TAZ rischia di interferire con impianti preesistenti o infrastrutture superficiali posti a valle rispetto allo stesso impianto oppure può interferire con l'impianto stesso tra pozzo di presa e pozzo di immissione a causa della troppa vicinanza (Thermal feedback – cortocircuitazione termica). È importante quindi sapere, soprattutto in fase di progettazione di un impianto, la futura estensione della TAZ.
A causa di questi rischi ed il crescente numero di sistemi GWHP si viene a creare la necessità di sviluppare nuovi criteri nelle politiche energetiche per le acque sotterranee che consentano di pianificare e distribuire tali impianti soprattutto in un territorio urbano. Vengono infatti qui proposti i risultati di diversi studi dedicati al fine di ottimizzare la progettazione ed il funzionamento dei sistemi GWHP.
Parole chiave: *energia geotermica, thermal feedback, impianti a pompa di calore geotermica, protezione risorse idriche, thermal affected zone*

1. Introduction

Energy is actually one of the central topics of the European development policies: the main issues are related to the reduction of emissions and the mitigation of climate change, which put human health and quality of life of citizens at risk (Regione Piemonte, 2015).

The objective concerning the de-carbonization of the European energy system is corroborated in the 2020 Climate and Energy Package and the following 2030 climate and energy framework which contain and outline the medium-long term objectives which consist of: i) downsizing 40% of emissions from so-called greenhouse gases compared to 1990 reference values; ii) electricity production for a share of 27% from renewable sources; iii) 27% improvement in energy efficiency (European Commission, 2014). These ambitious goals have further strengthened in the agreements signed during the last Paris climate conference (COP21), with the three general options based on: safety, environmental sustainability and economic sustainability. (ONU, 2015)

According to REN2018 (2018) modern renewable energy supplied approximately 10.3% of total global energy consumption for heat in 2015. Another 16.4% was supplied by traditional biomass, predominantly for cooking and heating in the developing world. While additional bio-heat, geothermal direct use and solar thermal capacities were added, growth was very slow. A large portion of energy use in buildings is related to heating and cooling. Energy demand for cooling is growing rapidly, and access to cooling is an issue for health and well-being. Renewables currently play a small role in providing cooling services, although there is considerable potential.

Geothermal energy is a reliable and constant source of energy. Despite the high capacity factor of traditional geothermal technologies, which exploit high enthalpy geothermal energy, the use of this energy is usually limited due to the local distribution of geothermal fields and the high up-front costs of drilling exploratory (Taddia *et al.*, 2018). However a notable contribution to the growth of this renewable energy is related and is expected to Ground Source Heat Pump systems (GSHP) which use the form of energy stored below the surface of the solid earth (low enthalpy geothermal energy). Low enthalpy geothermal energy, called also shallow geothermal energy is in fact available almost in every place and can be applied in various ways such as space heating and cooling. Depending on the use mode, energy can be extracted (heating) or injected (cooling).

Ground-source heat pump systems can then represent an important potential technology for mitigating greenhouse gas emissions related to space heating and cooling. Markets for heat pumps expanded around the world during 2017. Primary policy drivers for increased deployment of heat pumps include air pollution mitigation. The scale of the global heat pump market is difficult to assess due to the lack of data and to inconsistencies among existing datasets. It is estimated that air-source heat pumps make up the largest share of the global market, followed by ground source heat pumps. As of 2014 (latest data available), the global stock of ground-source heat pumps represented 50.3 gigawatts-thermal (GWth) of capacity, producing approximately 327 petajoules (91 TWh) of output (Lund and Boyd, 2016).

Based on historical growth rates, global ground-source heat pump capacity may have reached 65 GWth in 2017. The largest markets for heat pumps are China, the United States and Europe as a whole, where (in order of scale) France, Italy, Spain, Sweden and Germany were the most significant national markets in 2017 (REN21, 2018).

Two major types of ground-source heat pumps exist: closed loop heat pump systems (ground-coupled) or open loop heat pump systems (groundwater source) (Rafferty, 2000). Closed loop heat pump system also called ground-coupled system uses a buried earth coil with circulating fluid in a closed loop of horizontal or vertical pipes to transfer thermal energy to and from the ground. Open-loop heat pump system also called groundwater heat pump system (GWHP) need the presence of an aquifer as a heat source or sink.

GWHP systems extract groundwater from one or more wells, pass it through a heat exchanger or a heat pump, which either obtain heat from, or rejects heat, and discharge water back into the aquifer or nearby surface water. A typical open loop system scheme is represented by a well-doublet system which comprises three elements: an abstraction well, a heat-transfer system and one (or more) reinjection well(s) (Banks, 2009).

This reinjection disturbs the natural aquifer temperature, producing a local temperature anomalies (cold or heat plume) known as the thermal affected zone (TAZ). Such a thermal plume may pose an external risk to downstream users and environmental receptors or an internal risk to the sustainability of the well doublet, due to the phenomenon of thermal feedback.

Groundwater represents the world's largest and most important source of potable water. It is also an important resource for many of the world's larger cities. Urban and industrial development can impose major stresses on this resource on quality and on quantity, by increasing water demand (Howard, 2002). A balance between its use and protection has then to be found: to avoid detrimental environmental impacts, it is necessary to define groundwater temperature limits for heating and cooling and minimum distances between such geothermal systems. A long term effects of GWHP systems have also to be considered carefully in order to find a balance between system utilization and groundwater protection. (Haehnlein *et al.*, 2010).

Moreover, it is important to know if the TAZ can interfere with downgradient pre-existing plants or subsurface infrastructure or with the plant itself (thermal feedback). It is then important to know, even before constructing a GWHP system, the future TAZ extent around the planned injection point.

Due to these risks, the increasing number of GWHP systems enforces the need for new criteria to develop subsurface energy policies that allow planning their spatial distribution. Well-designed GWHP systems can optimize thermal energy extraction from the aquifers without causing undue environmental effects. To obtain these sustainability criteria, the results of different dedicated studies are here proposed, in order to optimize the design and operation of GWHP systems. The studies refer mainly to GWHP systems located in the outwash plain of Turin (Piemonte).

2. GSHP Systems basic principles

GSHP systems are environmentally friendly and energy efficient technologies that exploit the relatively constant temperature of the ground, or a medium thermally coupled to the ground, versus outside air temperature.

Air-source heat pumps have been used for many years for both space heating and cooling; however, their efficiency is influenced by the variation in outside air temperature. In winter, when heat is most needed, the outside air is cooler, thus often requiring backup electric resistance heating during the coldest days. Similarly, cooling is most needed during the hottest days, requiring the equipment to work at low efficiencies.

Ground-source heat pumps, overcome the problem of resource variations, as ground temperatures remain fairly constant throughout the year. Depending upon the soil type and moisture conditions, ground (and groundwater) temperatures experience little if any seasonal variations below about 10 m (fig. 1).

The ground-source or geothermal heat pump systems (GSHP or GHP), thus have several advantages over air-source heat pumps. These are: (1) a more stable energy source than air which implies good energy performances over the entire heating season, even with very low air temperatures when the performance of air source heat pump is poor; (2) they use less refrigerant and (3) do not require the unit to be located where it is exposed to weathering. The main disadvantage is the higher initial capital cost, being about 30 to 50% more expensive than air source units.

In particular, groundwater heat pumps (GWHPs) utilize the natural thermostability of groundwater. The diffusion of this kind of system is favored by different factors including plant and aquifer characteristics. Two main aquifer characteristics, which make GWHP diffusion attractive, are high productivity and good saturated thickness, which ensure good heat dispersion in a restricted area around the injection wells.

3. Groundwater heat pump system potential in Piemonte

Geothermal resources are abundant in Italy, ranging from resources for shallow applications (including heat pump technology), through to medium (> 90 °C) to high (> 150 °C) temperature systems at depths accessible only by wells (usually within 3-4 km) (Santilano *et al.*, 2015).

Geological bodies and groundwater in the Piemonte plain could represent an important source of clean geothermal energy and seemed particularly suitable for a wide implementation of GWHP direct open-loop systems (Lo Russo *et al.*, 2009). The average groundwater temperature ranges from 13.2 °C (minimum) to 15.5 °C (maximum), with a mean of 14.0 °C on a regional scale (Regione Piemonte, 2007).

3.1. Hydrogeological setting

Regione Piemonte (2005, 2007) studies documented the hydrogeology of the plain area with a high degree of confidence based on a large number of wells in the Turin area. As well known, an unconfined high-productivity aquifer connected to the surface water drainage network is found across the entire Piemonte plain and in the major valleys in the mountain sector. This unconfined aquifer is constitute by various continental units results of different exogenous processes linked to Quaternary glacial and alluvial dynamics (fig. 2). Generally, these units are lithologically represented by coarse gravel and sandy sediments (locally cemented) with limited amounts of thick clayey-loamy horizons related to lacustrine facies. Confined productive aquifers are also widespread they represent the main regional source of water for human consumption (Civita *et al.*, 2004). The vertical separation between the unconfined and deeper confined aquifers varies from a few meters to several tens of meters depending on local hydrogeological conditions. (Lo Russo *et al.*, 2009).

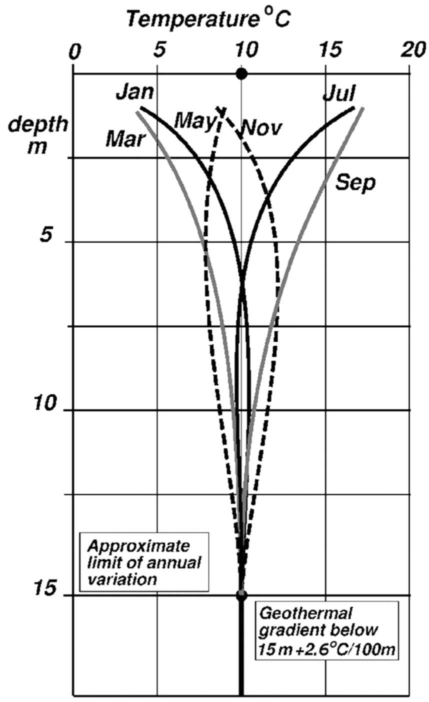

Fig. 1. Seasonal variation of the near-surface temperature profile respect the progressive depth (Busby *et al.*, 2009).
Variazione stagionale della temperatura con la profondità (Busby et al., 2009).

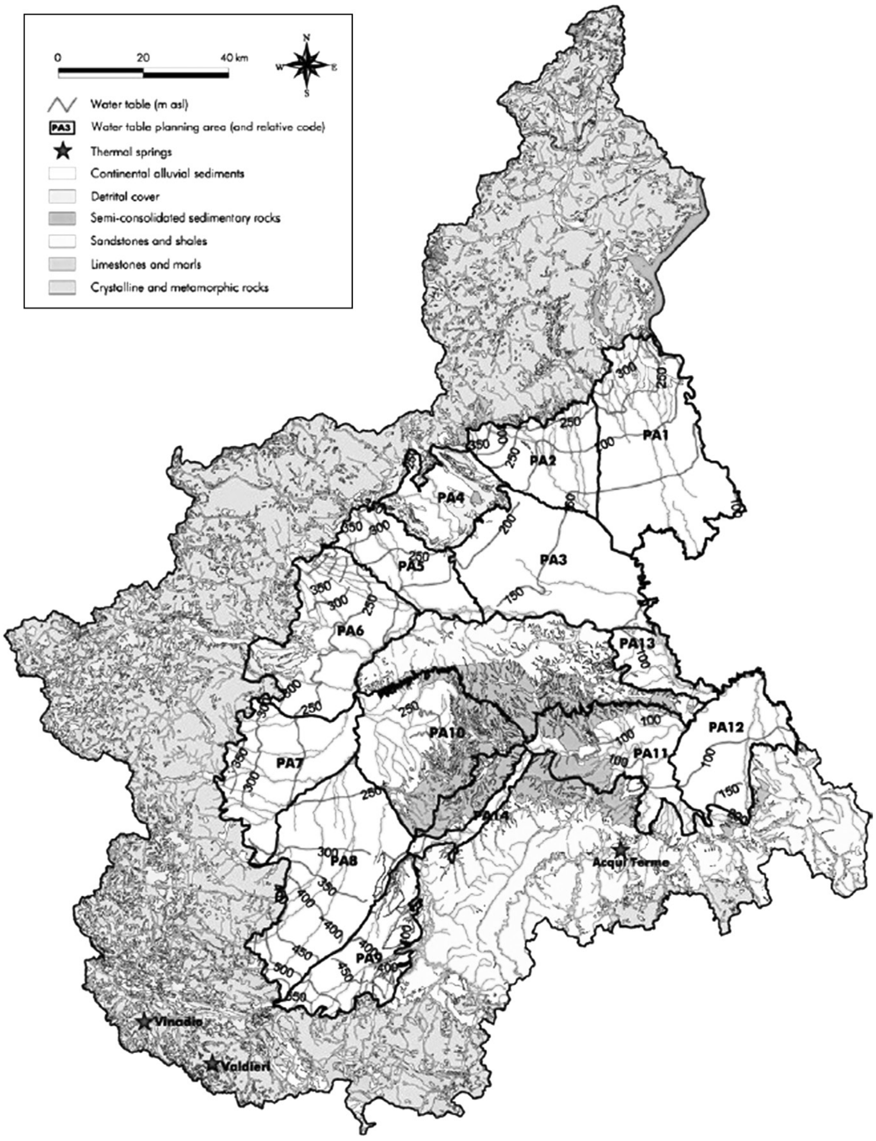

Fig. 2. Hydrogeologic map of Piemonte (modified after Civita *et al.*, 2004).The unconfined aquifer is indicated by white color (Continental alluvial sediments) while grey line indicates the water table elevation.
Mappa idrogeologica del Piemonte (modificata dopo Civita et al., 2004).
L'acquifero non confinato è indicato con il colore bianco (sedimenti alluvionali continentali) mentre la linea viola indica la piezometria.

3.2. Water quality

An open loop system does not necessarily require water of high quality otherwise depending upon its specific chemistry, it can promote scaling, corrosion or both. If the water has a tendency to be scale forming, fouling of the heat exchanger may occur. The fouling reduces the effectiveness of the heat exchanger and compromises the performance of the heat pump. In most cases, the formation of scale is a slow process occurring over months or years. As a result, the impact of the reduced heat pump or desuperheater performance on the utility bill is gradual. This slow erosion of the savings the system would otherwise produce may be imperceptible to the system owner (Rafferty, 2000).

According to Lo Russo *et al.* (2009) which examined the chemical analyses of the waters derived from the shallow aquifer, performed twice a year since 1990 through the regional groundwater-monitoring network, in general, water quality at the regional scale is good enough to be used without the need for secondary exchangers in the heat pump systems. In exceptional cases (i.e. in the more polluted sites) groundwater quality is unsuitable to be used directly and secondary exchangers are recommended.

This technical option would significantly affect both the capital and running costs of the heat pump plant. For this reason, the characteristics of a prospective site (including water chemistry) should be carefully studied before choosing the heating system in order to verify the real economic benefit of installing a GWHP system.

4. Main constrain in development of GWHP systems

4.1. Groundwater protection

It is known that changes in groundwater temperature can influence its physical properties, chemical reactions, microbiology of the aquifer (Hanlein *et al.*, 2010). However, the risks have not been widely concerned and comprehensive studies are needed (Zhu, 2017).

Proper regulations to guarantee groundwater protection are in place in the countries with a developed GWHP market. In Piemonte deep, high-quality groundwater bodies are legally preserved for human consumption. To avoid potential pollution GWHP could be used only with shallow groundwater. Nevertheless, where the local hydrogeological conditions are such that no confined aquifer is present below the water table or the top of the confined aquifer is below 60m depth, it may be appropriate to consider 60 m as the maximum depth for injecting GWHP discharges. (Lo Russo *et al.*, 2009).

4.2. Planning of GWHP in urbanized area

The integration of GWHP systems into urbanized area will depend on a series of factors that should be taken into account to determine the feasibility of the installation. In particular, if compared to less anthropized areas, some elements require particular attention as underground availability and building restrictions, which play a determinant role for the installation of this type of system. This interaction between the buildings, the city's framework and the underground infrastructures (garages and parking areas, cellars, and communication, and transport systems such as tunnels, metros, and trains) has to be examined as they could influence the choice of the most suitable type of plant and then development of such kind of low enthalpy geothermal systems.

Due to the high concentration of buildings, the extensive use of ground and consequently the limited free ground, two important issues to be considered are:

- the interference that could occur between different GWHP plants
- the risk of thermal feedback in a well-doublet system.

Considering a well-doublet system if the designed distance between abstraction and rejection well is not enough there is in fact a risk that a proportion of the discharged warm water will flow back (against the regional hydraulic gradient) to the abstraction well, resulting in a reduction of the provided energy performance. This phenomenon is called thermal feedback. Thermal feedback risks can be avoided by a relatively large separation between the abstraction well and re-injection tool. This distance is typically unrealistically large for many densely inhabited urban areas. The temperature of the abstracted water will thereafter rise over time, towards a value described by Gringarten and Sauty (1975). At best, this gradually compromises the efficiency of the cooling scheme and at worst it can result in system failure or environmental non-compliance. In other words, far from being a "renewable" cooling source, the system can eventually become unsustainable (Banks, 2009).

Thermal feedback problem that has been widely described in literature (Ferguson and Woodbury, 2005; Banks, 2009; Milnes and Perrochet, 2013). To avoid this problem Lo Russo *et al.* (2016) proposed the use of gabiondrains as alternative reinjection systems to reduce the distance to the abstraction well and avoid thermal feedback in cases where abstraction withdrawal through the well occurs in deeper regions of the aquifer.

5. Modelling of the thermal affected zone: best practice

Different authors suggested that the thermal plume dimension around an operating well is site-specific and can critically affect neighboring injection or production wells. In addition, the environmental impact can be notable, particularly where open-loop plants are located adjacent to each other. Thus, GWHP systems are recommended to be installed in areas, where the interference can be avoided, or rigorous and proactive management of multiple adjacent GWHP systems is warranted (Pophillat, 2018).

Quite apart from building design considerations, proper installation and effective maintenance of GWHP plants requires an appropriate characterization of subsurface heat transport processes such as conduction and convection. (Hecht-Mendez *et al.*, 2010).

Numerical modeling studies should be carried out to analyze the behaviour of the aquifer during the design phase of an installation of GWHP system. This would assist in the correct evaluation of the subsurface environmental effects and avoid interferences with previously existing groundwater uses (wells) and subsurface underground structures or the thermal feedback phenomenon. Here are presented the results of some previous studies, which analyses the steps that should be considered when approaching a numerical modelling. These case studies refer to some plant located in Turin plain which interest the unconfined aquifer. The numerical modelling were performed using the finite-element FEFLOW® package developed by Diersch (2005).

A sensitive analysis of the subsurface hydrogeological and thermal parameters affecting the TAZ was performed by Lo Russo *et al.* (2012). The parameters subjected to sensitivity analysis are: hydraulic conductivity (vertical and horizontal), natural hydraulic gradient, porosity, storativity, volumetric heat capacity of fluid (water) and solid (aquifer matrix), heat conductivity of the fluid and solid and longitudinal and transversal thermal dispersivity.

The parameter sensitivity was performed by recalculating the TAZ for variations of each parameter (10% or 20% reduction and 10% or 20% increase with respect to the initial value) one at a time. In order to compare the results of the sensitivity analysis, TAZ was defined by the maximum extent of

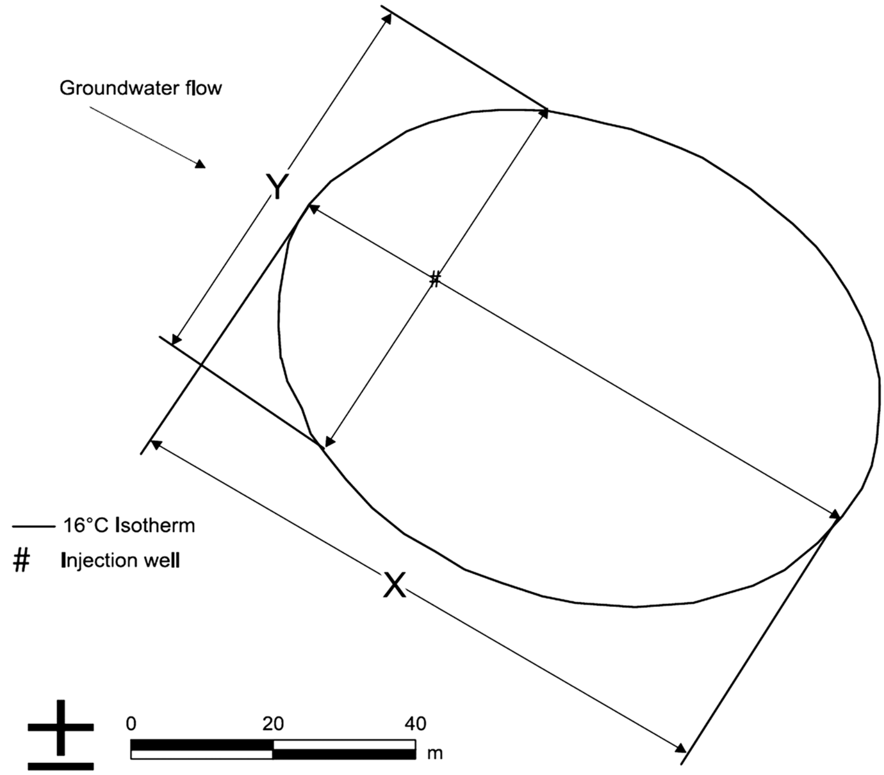

Fig. 3. Geometric parameters of the TAZ. The X axis was measured along the groundwater flow direction, and the Y axis is the normal axis passing over the injection well (Lo Russo *et al.*, 2012).

Parametri geometrici della TAZ. La lunghezza X è misurata lungo la direzione di flusso dell'acquifero e la lunghezza Y è misurata perpendicolarmente alla direzione di flusso passante per il semiasse maggiore dell'ellisse (Lo Russo et al., 2012).

the 16 °C isotherm in the ellipsoid thermal plume (fig. 3). The total surface area enclosed by the 16-°C isotherm was computed and the length of each ellipsoid axis at the injection well was also measured.

The results of the analysis indicate that the hydrodynamic parameters correlated with groundwater flow such as the hydraulic conductivity and the gradient are highly important. The size of the TAZ is also most sensitive to variations in volumetric heat capacities of the fluid and the solid while the effects of variations in the storativity and the thermal conductivities of the fluid and solid seem to be almost negligible.

In order to accurately predict the TAZ, another important issue which has been analyzed is the introduction of parameters time variability. As the actual flow rate and injection temperature are highly time-variable and follow changes in building energy requirements, it is then necessary to consider this time variability. Lo Russo *et*

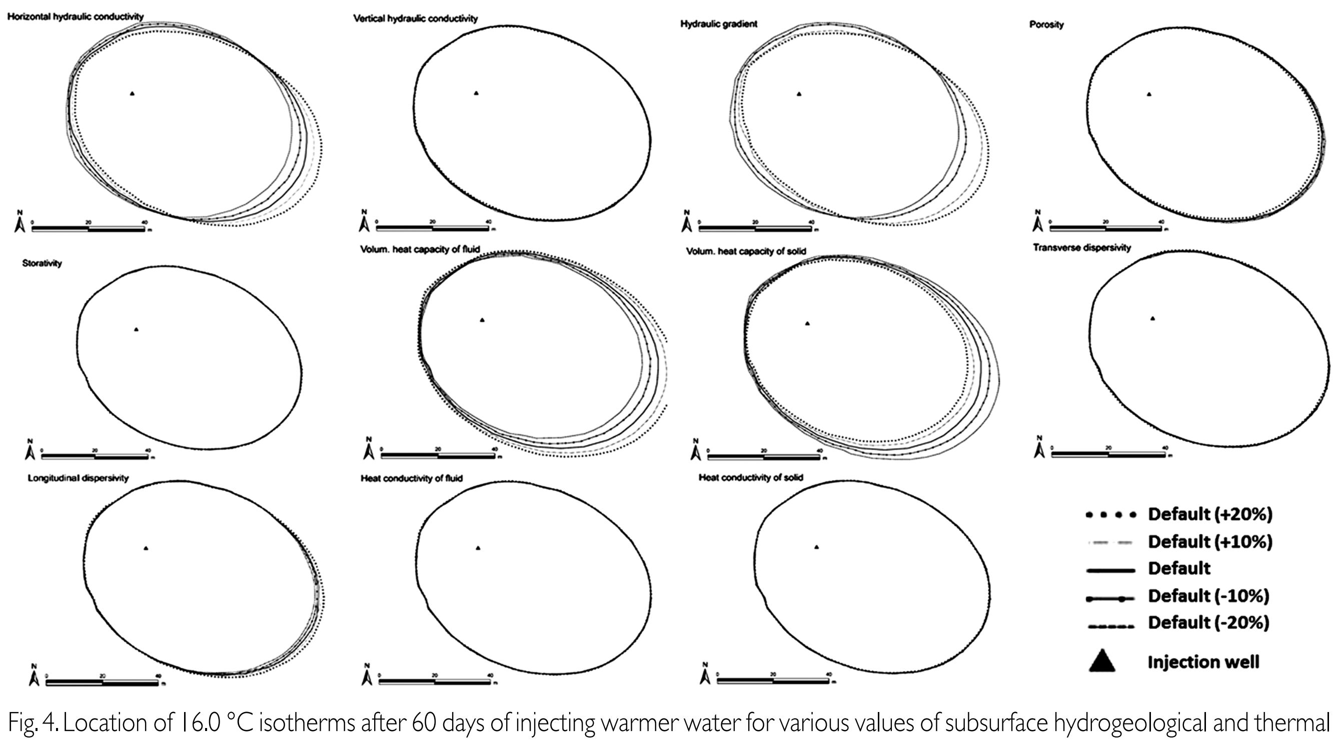

Fig. 4. Location of 16.0 °C isotherms after 60 days of injecting warmer water for various values of subsurface hydrogeological and thermal parameters (modified from Lo Russo *et al.*, 2012).

Isoterma 16°C dopo 60 giorni di immissione di acqua calda in acquifero in stato transitorio con parametri termici e idrogeologici variabili (modificato dopo Lo Russo et al., 2012).

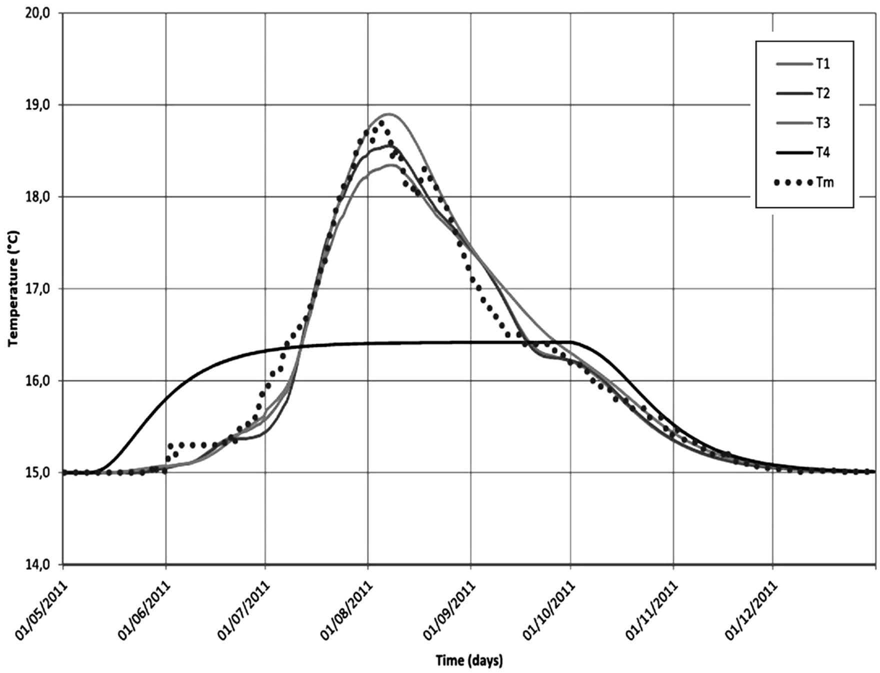

Fig. 5. Temperatures in piezometer S2. The dotted line corresponds to the measured data.
Temperatura nel piezometro S2. La linea puntinata corrisponde ai dati misurati.

al. (2014) verified whether the time-averaged values of flow rate and temperature can be suitable substitutes for hourly values. Even in this case the TAZ extension has been conventionally indicated by the 16.0 °C isotherm (fig. 4). It was determined the extent to which these simplifications modify the reliability of TAZ predictions: if the use of average hourly (T1), daily (T2), monthly (T3) or seasonally (T4) injection flow rate and temperature data produced good quality simulation results. To confirm the reliability of the simulations the four simulation results were then compared with groundwater temperature data measured using a downgradient piezometer in order to assess the reliability of the simulations (fig.5).

Simulations T1, T2, and T3 were statistically tested to quantitatively evaluate their reliability. Scenario T4 was not tested because the results were clearly too far from the measured data for meaningful statistical comparison.

The quality of the simulation was satisfactory when hourly, daily, or monthly flow rate and injection temperature data were used, whereas the seasonal averages were not suitable for reliably assessing TAZ development (Lo Russo *et al.*, 2014).

Another important parameter which can influence the TAZ extension is the dynamic viscosity. As known hydraulic conductivity has a major influence on heat transport because plume propagation occurs primarily through advection. Hydraulic conductivity is, in turn, influenced by water reinjection because the dynamic viscosity of groundwater varies with temperature. Lo Russo *et al.*, 2016 evaluated then how the thermal-affected zone (TAZ) is influenced by the variation in dynamic viscosity due to reinjected groundwater in a well-doublet scheme. A computational analysis using FEFLOW software have been conducted.

Usually the dynamic viscosity of groundwater is set at a constant value. This scenario of constant condition (FEFLOW program default) is used as a reference setting (scenario SC2) for comparison with TAZ calculations determined when dynamic viscosity varies with reinjected groundwater temperature.

The TAZ area was graphically

Tab. 1. Geometric parameters of the TAZ calculated for each case study and comparison between SC1 and SC2 (Lo Russo *et al.*, 2018).
Parametri geometrici della TAZ calcolati per ogni caso studio e confrontati tra SC1 e SC2 (Lo Russo et al., 2018).

Parameter	*K* value	SC 1 variable dynamic viscosity			SC 2 constant dynamic viscosity			Comparison between SC1 and SC2		
		$\Delta T = +$ 5 °C	$\Delta T = +$ 10 °C	$\Delta T = +$ 15 °C	$\Delta T = +$ 5 °C	$\Delta T = +$ 10 °C	$\Delta T = +$ 15 °C	$\Delta T = +$ 5 °C	$\Delta T = +$ 10 °C	$\Delta T = +$ 15 °C
Area [m^2]	K_{xy} 1×10^{-4}	6,962.25	8,479.67	9,280.52	6,961.11	8,447.95	9,264.16	ΔTAZ[a] = −0.02%	ΔTAZ = −0.4%	ΔTAZ = −0.2%
	K_{xy} 1×10^{-3}	6,895.90	8,501.98	9,696.49	6,872.01	8,478.98	9,449.19	ΔTAZ= −0.3%	ΔTAZ = −0.3%	ΔTAZ = −2.6%
	K_{xy} 1×10^{-2}	5,662.53	18,286.86	27,796.96	5,543.00	17,150.89	25,114.42	ΔTAZ = −2.1%	ΔTAZ = −6.2%	ΔTAZ = −9.7%
X	K_{xy} 1×10^{-4}	94.48	104.41	109.25	94.46	104.23	109.22	$\Delta X = 0.02$	$\Delta X = 0.18$	$\Delta X = 0.03$
	K_{xy} 1×10^{-3}	123.33	138.29	149.58	121.68	135.76	143.97	$\Delta X = 1.65$	$\Delta X = 2.53$	$\Delta X = 5.61$
	K_{xy} 1×10^{-2}	279.24	525.51	610.97	276.75	505.86	578.10	$\Delta X = 2.49$	$\Delta X = 19.66$	$\Delta X = 32.87$

[a] ΔTAZ is equal to TAZ_{SC2} variation with respect to TAZ_{SC1} [%]

defined as the maximum plant extent of the 16°C isotherm in the thermal plume. The total surface area enclosed by that isotherm was computed. The length of the TAZ area along the groundwater flow direction (X) was also measured (fig. 3).

For both scenarios (SC1 and SC2), nine different cases have been considered using combinations of three conductivity classes and three different injection temperatures values. For each conductivity class, three injection temperatures were considered (tab. 1). The temperatures were set to explore the real potential functioning conditions of the heat pump (Lo Russo *et al.*, 2016).

The modeling results demonstrate non-negligible groundwater dynamic viscosity variation that affects thermal plume propagation in the aquifer. This influence on TAZ calculation was enhanced for aquifers with high intrinsic permeability and/or substantial temperature differences between abstracted and post-heat-pump-reinjected groundwater.

6. Conclusions

Global energy demand is going to grow in the next decades. Distribution and typology of energy demand is rapidly changing. Fossil conventional sources consumption will grow as well as renewables. In this context low-enthalpy geothermal resources represent a very promising technology to provide cooling and heating needs for buildings. Groundwater can be used directly to such aims by ground water heat pump systems.

Their use has to be taking into account especially where unconfined aquifers have high productivity characteristics as most of the flood plain areas. Turin plain represents a good chance for the potential exploitation of this technology. However, groundwater has to be considered not only a potential source of energy but also an important source to be protected. In this regard numerical modelling is an important modern tool that can predict environmental effects prior to construction of the plant and to assess the effects of warmer (or colder) water injection.

The parameters connected with the groundwater flow influence the TAZ development, particularly those connected with the advective component of heat flow. Consequently, the hydrodynamic subsurface parameters are of major importance to reliable modelling of the TAZ, and on-site investigations should concentrate determining these parameters (hydraulic conductivities and gradient, porosity, etc.) (Lo Russo *et al.*, 2012).

For significant GWHP plant projects, in order to obtain a good match between simulated and actual groundwater temperatures during modeling of the TAZ produced by a GWHP plant, suitable pumping tests and a potentiometric surface determination appear necessary in all cases.

Also the variation in dynamic viscosity with groundwater temperature can have a significant influence on the geometry and extension of the TAZ, especially when high aquifer hydraulic conductivity and/or relatively warm injected water are involved. Therefore, at least in these modeling contexts, dynamic viscosity variance should be taken into account to enable accurate assessment of subsurface thermal perturbation (Lo Russo *et al.*, 2018).

Moreover, Lo Russo *et al.*, (2014) demonstrated that in order to obtain a good match between simulated and actual groundwater temperatures during modeling of the TAZ produced by a GWHP plant, it is necessary to model the injection using realistically variable flow rates and injection temperature data. As well-known time-averaging reduces the computational effort required in modelling routines and is therefore extensively used in professional practice for TAZ prediction. Otherwise, only the use of average hourly, daily, or monthly injection flow rate and temperature data produced good quality simulation results. In contrast, the use of seasonal average values did not produce good estimates of the TAZ. Simulations employing seasonal average data might produce unreliable results, underestimating the peak temperature reached by the groundwater in the neighbourhood of the injection well, and therefore should be avoided if possible. Instead, the use of hourly, daily, or monthly data may be considered a good option for TAZ modelling (Lo Russo *et al.*, 2014).

The knowledge of the hydrodynamic parameters and the plant running functioning conditions are requirements to provide reliable results. These issues should be taking into account when developing technical guidelines for the wide implementation of the technology.

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